Present Status of Nuclear Cross Sections and Possibilities at RIA

Stephanie Frankle, Bob Little, Dave Madland, and Phil Young
Los Alamos National Laboratory

Rare Isotope Accelerator Workshop, October 30, 2000
LA-UR-00-5123

Abstract

- Radiation Transport codes such as MCNP/MCNPX are used to simulate the interaction of neutrons, photons, and light charged particles with materials for a wide range of applications. Each community of users has their own special interests. To serve them all, our transport codes need accurate nuclear data libraries based on evaluated data. Evaluated data is a mixture of both experimental data and theoretical modeling (theoretical modeling is heavily relied upon for secondary particle emission probabilities and their distributions). We need evaluated data for interactions of n, γ, p, d, t, ^{3}He and α with nuclei from H to Cm, *both* stable and unstable.
- RIA can access cross-section information directly for some reactions, or by inverse scattering. Additionally, information from experiments can have a large impact on the theoretical modeling efforts by helping us to obtain the correct optical model potential and level densities, for example, to predict cross sections and secondary particle production information where experimental data are not available.

Topics

- Radiation Transport Codes and Applications
- Evaluated Nuclear Data
- Experiments at RIA to support the evaluated nuclear data efforts at LANL (and elsewhere)

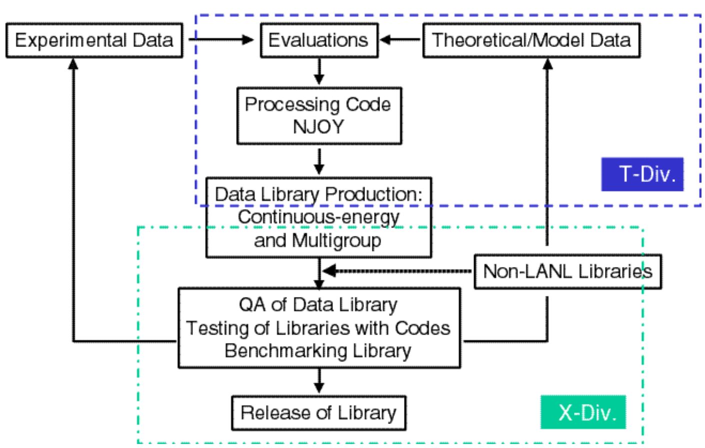
Radiation Transport Codes

- Radiation Transport codes such as MCNP/MCNPX are used to simulate the interaction of neutrons, photons, and light charged particles with materials for a wide range of applications.
  - » Criticality Safety
  - » Nuclear Reactor community
  - » Medical Physics
  - » Environmental Assessment - Nuclear Well-logging
  - » Other diagnostic applications

Applications

- Each community of users has their own special interests
- To serve them all, our transport codes need accurate nuclear data libraries based on evaluated data.
- An evaluation must contain the following as a function of incident particle energy (0-150 MeV):
  - » Cross sections for all possible reactions
  - » All secondary particles from each reaction
    - Energy distributions
    - Angle distributions

Experiment to Data Library



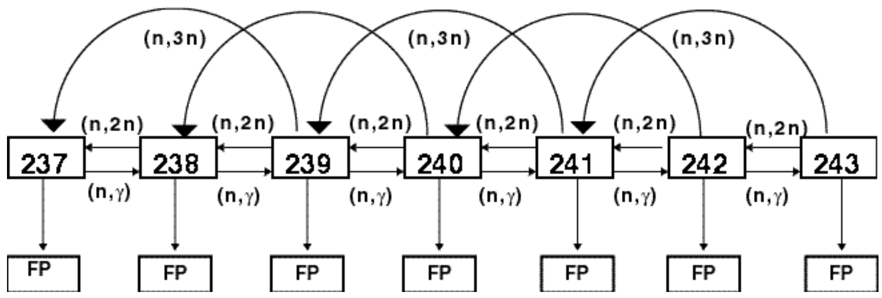
Evaluated Nuclear Data

- Experimental data does not exist for even one evaluation over such a large energy region.
- Evaluated data is therefore a mixture of both experimental data and theoretical modeling
  - » Theoretical modeling is heavily relied upon for secondary particle emission probabilities and their distributions
- We need evaluated data for interactions of n, γ, p, d, t, ^{3}He and α with nuclei from H to Cm, *both* stable and unstable nuclei
  - » Particular interest in nuclei used as radiochemical tracers in many applications and actinides and their fission products

Actinides

- The criticality safety and reactor communities have a strong interest in production and depletion of actinides and their fission products by neutrons.
  - » Has a great impact on their regulatory constraints / lifetime issues
- Many actinides are short lived and accurate prediction of production/depletion is difficult as the evaluated data do not exist or are of unknown quality.
  - » The same is true of fission products.
- *Need high quality data for incident neutrons on actinides and their fission products.*

Production and Depletion



Fission Products

- Definitions
  - » *fission fragment*: nuclear species existing at the scission point and just beyond, but prior to the emission of prompt neutrons.
  - » *fission product* (sometimes primary fission product): nuclear species formed after prompt neutron emission has occurred, but before any beta decay has occurred.
  - » *secondary fission product*: nuclear species formed from a primary fission product that has undergone at least one beta decay.
- The general term *fission product* is used when referring to either primary or secondary fission products or a combination of such products.

Time Dependence of Fission Products

- » nucleon orbit time in fission fragment: 6×10^{-22} sec
- » fission-fragment acceleration time (Coulomb repulsion): $\sim10^{-20}$ sec
- » prompt fission neutron emission time: 10^{-21} to 4×10^{-14} sec
- » beta decay (weak interaction) times of primary fission products: 0.08 - 58.2 sec half-lives

- Thus, a fission fragment lives as long as 4×10^{-14} sec, a primary fission product lives in the range 4×10^{-14} sec to 58.2 sec, and a secondary fission product lives from 80 millisec and beyond [this is all modulo half-lives as a time index].

Energy Release in Fission

- The energy release in binary fission, E_r, is by definition equal to the mass of the compound fissioning nucleus, M_c, minus the masses of the light, M_L, and heavy, M_H, fission fragments.
- By conservation of energy

$$E_r = (T_L + T_H) + (E_L^* + E_H^*) - (E_n + B_n)$$

  - » where T refers to the fission-fragment kinetic energy, E* refers to fission-fragment excitation energy, and E_n and B_n are the kinetic energy and binding energy of the neutron inducing fission.
- Examples:
  - » $^{236}U \rightarrow {}^{96}Sr + {}^{140}Xe$, E_r =188.692 MeV
  - » $^{236}U \rightarrow {}^{93}Rb + {}^{143}Cs$, E_r =183.722 MeV
  - » $^{236}U \rightarrow {}^{99}Y + {}^{137}I$, E_r = 190.662 MeV

Kinetic Energy Distribution of Fission Fragments

- In binary fission, momentum conservation yield:

$$\frac{T_L}{T_H} = \frac{M_H}{M_L}$$

- And the total fission-fragment kinetic energy is given by

$$E_f^{tot} = T_L + T_H$$

- Typical mean values for $n_{thermal}$ + ^{239}Pu are
  - » $\langle M_L \rangle = 100.4$ and $\langle T_L \rangle = 103.01$ MeV
  - » $\langle M_H \rangle = 139.6$ and $\langle T_H \rangle = 74.09$ MeV
- Roughly 1 in every 500 fissions is ternary for low energy neutrons.

Fission Products in Various Transport Codes

- Fission products are modeled in a variety of ways in transport codes. Two methods are
  - » A single average fission product for a given actinide like ^{235}U
  - » Detailed calculations as a function of time of the specific fission products produced and updating of material composition in a simulation
    - Need complete evaluation for every single fission product!
  - » Even for an average fission product treatment you need very good evaluations for a host of fission products, most of which are short-lived and unstudied

What do we need to know about fission products?

- Energy release in fission as a function of incident neutron energy
  - » de-excitation of fission fragments
  - » kinetic energy distribution of fission fragments
- Mass and charge distributions of fission fragments and products
- Motion of fission products in various materials
- Optical Model Potential (OMP) for neutron scattering by fission-fragment and fission-product nuclei
- Nuclear level densities of fission-fragment and fission-product nuclei

What can be done at RIA?

- Produce beams of various fission products for $^{235,238}U$, ^{239}Pu, and other actinides
  - » Measure the energy loss (-dE/dx) and range (R) of fission products moving in neutral and charged media: ^{4}He and ^{208}Pb
    - While the fission-product heavy-mass peaks for the three systems are approximately the same, the corresponding light-mass peaks are shifted relative to each other. None of the peak fission product nuclei are explicitly treated in the extensive heavy-ion studies of Ziegler. However, a number of studies have been done using a ^{252}Cf source and this work would be the starting point for RIA studies.
  - » An important quantity to determine is the fission-product effective charge Z_{eff} in the various media.

Fission Product Experiments cont.

- Reactions on various scales
  - » Coulomb excitation of atomic nuclei by fission product nuclei with charge Z_{eff} (nuclear scale).
  - » Single atom knock-out reaction by a fission-product nucleus near the surface of a material (atomic scale).
  - » Atomic cluster knock-out reaction induced by a fission-product nucleus near the surface of the medium (molecular scale).
- Optical Model Potential for neutron scattering
  - » Almost total lack of measured elastic scattering observables for fission products and the large extrapolations in isospin that must be made in existing potentials

Fission Product Experiments cont.

- OPM measurements
  - » Measure elastic proton scattering using inverse scattering of a gaseous/liquid target to obtain OMP
  - » Obtain corresponding neutron microscopic OMP by turning off Coulomb force and reversing sign of 3-component of the isospin
    - Then one can calculate realistic compound-nuclear formation cross sections for prompt neutron emission in fission (Los Alamos Model)
    - As well as elastic scattering cross sections and transmission coefficients for use in Hauser-Feshbach calculations for neutrons interacting with the fission product
- Nuclear level density studies using the same inverse scattering technique; transfer and charge-exchange reactions

Other Short-lived Nuclei

- In the same manner as discussed for actinides and fission products, experiments can be performed for short-lived nuclei of interest to the radiochemical community.
- Samples are placed in experiments, retrieved and analyzed to determine the isotopic makeup of sample after irradiation. A combination of this isotopic analysis with production and depletion cross sections allows a neutron spectrum, for example, to be inferred.
  - » Hence the same information needed for fission products are also needed for these nuclei.

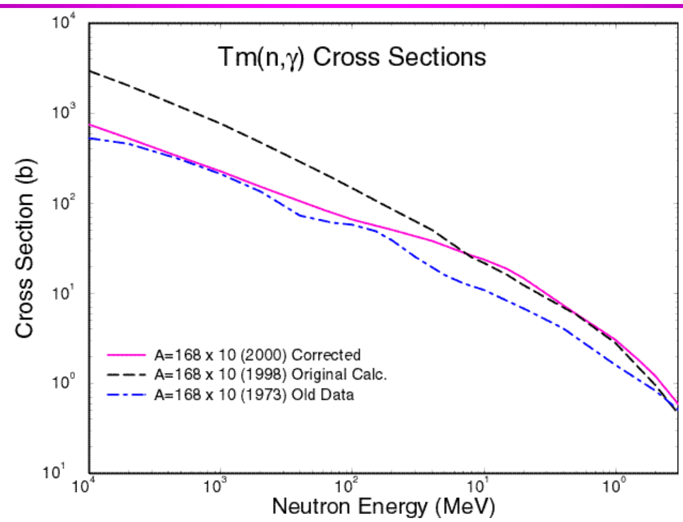
Optical Model Potential - Odd A

- Odd-A Isotopes
  - » Clear rotational band structure
  - » High quality coupled-channels (CC) optical model potential determined from ^{169}Tm (and ^{165}Ho) scattering and total cross section data.
  - » Good agreement with s-wave neutron strength function experimental data.

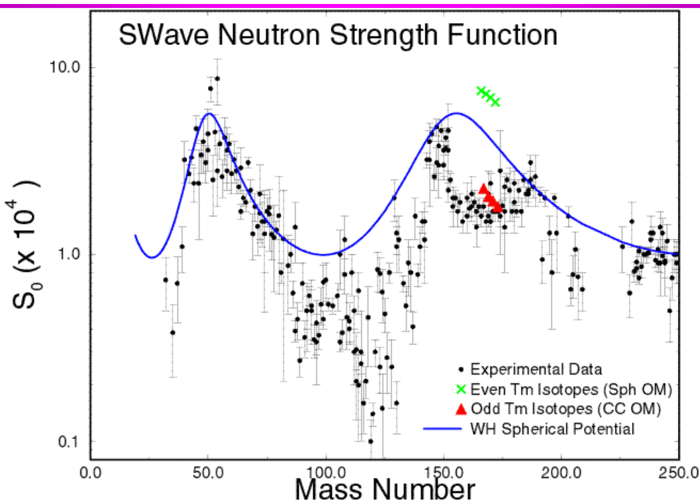
Optical Model Potential - Even A

- Even-A Isotopes
  - Odd-Z, odd-N nuclides ➔ complicated nuclear structure
  - Originally used spherical optical potential derived from the CC potential by means of a simple approximation (increase W_d by 20%).
  - Approximation appears reasonable above 100 keV but gives too much reaction cross section at lower energies ➔ s-wave neutron strength functions much too large.
  - Rough approximation is to simply average the ^{167}Tm and ^{169}Tm transmission coefficients for use in the ^{168}Tm + n calculations with GNASH.
  - New dispersive (coupled-channel) optical model potential should be developed.

Effect of different OMP's on ^{168}Tm



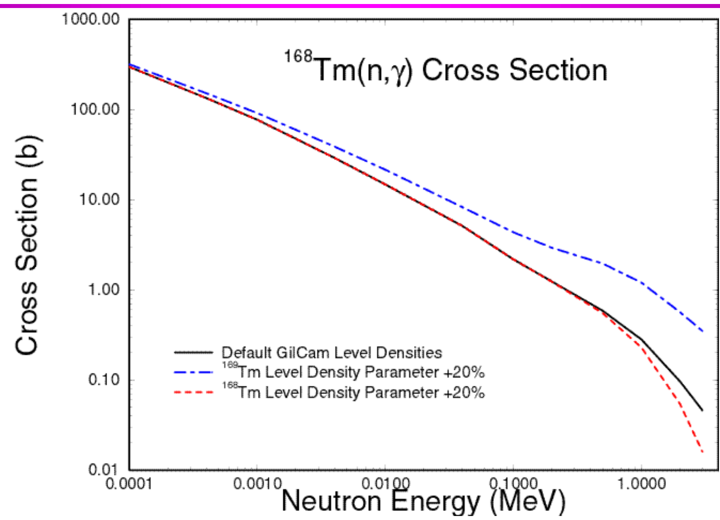
Effect of different OMP's on Tm isotopes



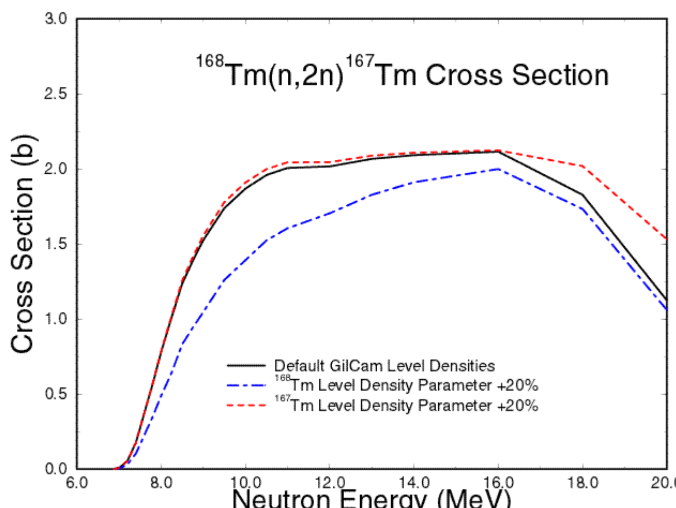
Level Densities

- Important component of nuclear model calculations.
- Several different models and parameterizations available.
- We typically use a constant-temperature plus fermi-gas model for lower energy calculations and a modified form with energy-dependent level density parameters at higher energies.
- Level density parameters are typically not well known except for a selection of common stable isotopes for which data exists.
- Certain cross sections are very sensitive to level densities. For example:
  - » (n,γ) cross sections above the competing (n,n') threshold,
  - » (n,xn) cross sections near threshold,
  - » and (n,x) and fission cross sections.

Effect of a change in level densities on ^{168}Tm(n,γ)



Effect of a change in level densities on ^{168}Tm(n,2n)



Light Charged Particle Reactions

- We are also interested in the interaction of n, γ, p, d, t, ^{3}He and α interacting with stable and unstable light nuclei - from H to O.
- Reaction cross-sections and all secondary-particle distributions.
- n, γ, p, d, t, ^{3}He and α +
  - » p, d, t
  - » ^{3,4,5,6}He
  - » ^{6,7,8,9}Li
  - » ^{7,9,10,11,12}Be
  - » ^{10,11,12}B
  - » And so on…..

Summary

- Ultimate goal is to have complete evaluations (suitable for radiation transport codes) for n, γ, p, d, t, ^{3}He and α interacting with *both* stable and unstable nuclei from H to Cm.
- Experimental data that gives us direct information on the reaction cross-sections and secondary particle distributions, or that assists in defining the parameters used in the various nuclear model codes, is crucial.